AUTOMATIC COMPENSATION OF FIRST - ORDER POLARIZATION MODE DISPERSION IN A 10 Gb/s TRANSMISSION SYSTEM

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Abstract: We demonstrate a novel, adaptive optical polarization mode dispersion equalizer in a 10-Gb/s transmission experiment. The equalizer comprises a fast electrooptic polarization transformer, an adjustable differential polarization delay line, and a simple electric distortion analyzer for automatic feedback control.

Introduction

Polarization mode dispersion (PMD) in optical fibers can severely impair the signal quality in high-bit-rate long-distance lightwave systems. The largest distortions generally arise from first-order PMD, which creates a delayed echo of the original signal in the fiber due to the different group velocities of the two principal states of polarization (PSP) /1-2/. While modern single-mode fibers exhibit negligible PMD, with average differential group delays (DGD) of the order of 0.1 ps/km$^{1/2}$, some of the older fiber cables - in particular those embedded in terrestrial networks - can show large PMD effects with average DGD's of up to 2 ps/km$^{1/2}$ /3/. Moreover, the instantaneous DGD in such high-PMD fibers generally fluctuates randomly with time, and hence, can temporarily exceed values of more than 100 ps for transmission distances of only a few hundred kilometers, which may lead to a complete eye closure in a 10-Gb/s signal /4/.

Several methods for reducing the adverse effects of first-order PMD have been investigated previously, including adaptive electrical distortion equalizers as well as all-optical PMD compensators /5-8/. Although electrical equalizers may also reduce other distortions in the received signal, they cannot completely eliminate the impairments caused by first-order PMD /5/. Adaptive polarization-diversity receivers and optical PMD compensators, on the other hand, are capable of completely removing the distortions due to first-order PMD from the optical signal - at least over a narrow optical bandwidth /6-8/.

Moreover, optical PMD compensators usually operate independent of the optical receiver and, hence, can be readily adapted to different signal rates or formats. Optical compensation of first-order PMD is accomplished by introducing a variable time delay between two adjustable orthogonal polarization states in the optical signal. In this paper we demonstrate, to our knowledge for the first time, a fully automatic optical PMD equalizer that adaptively compensates for randomly fluctuating first-order PMD in optical transmission fibers. We have tested the performance of this compensator in a 10-Gb/s transmission experiment employing a high-PMD fiber with an average DGD of 50 ps.

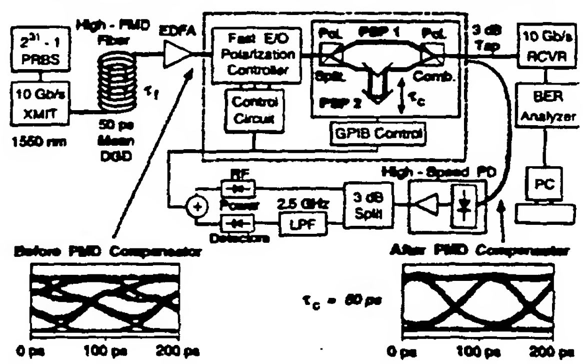
Principle of Operation

Fig. 1 displays a schematic diagram of our automatic PMD compensator employed in a 10-Gb/s transmission experiment. The compensator comprises a fast electrooptic polarization controller (POLCON) which connects the output of the transmission fiber to the input of a variable differential polarization delay line (DPDL). The output of the DPDL is coupled to a high-speed monitor detector, which measures the PMD-induced distortion in the output of the compensator and generates a feedback control signal for the POLCON and the DPDL.

The DPDL splits the output light of the POLCON into two orthogonally polarized components, then delays these components relative to each other by a variable time, τ_c and finally combines them again into a single output fiber. The DPDL thus generates variable first-order PMD with continuously adjustable DGD, $\tau_c = 0$ to 120 ps, which is introduced between the two orthogonal eigenstates of the polarization splitter in the DPDL. Furthermore, the adjustable POLCON transforms the time-varying output PSP's of the transmission fiber into the fixed eigenstates of the DPDL, in such a way that the polarization component transmitted in the fast PSP of the fiber is transformed into the slow eigenstate of the DPDL and *vice versa*.

Thus, if the differential time delay, τ_c, introduced in the DPDL is exactly equal to the DGD, τ_f, in the transmission fiber, then the optical signal after the compensator is completely free of distortions due to first-order PMD.

Fig. 1: Experimental setup for fully automatic adaptive compensation of first-order PMD in a 10-Gb/s NRZ transmission system, showing an example of a received eye diagram with and without automatic PMD compensation.



If however the PSP-transformation and/or the time delay, τ_c, is not properly adjusted, then the output signal of the compensator will exhibit first-order PMD with a residual DGD, τ_{tot}, of

$$\tau_{tot} = \sqrt{\tau_f^{\,2} + \tau_c^{\,2} + 2\tau_f \tau_c \cos(2\theta)}\,,$$

where 2θ is the angle between the Stokes vectors of the fast PSP's of the fiber and the PMD-compensator /4/. We may thus find the desired PSP-transformation and the time delay,

τ_c, by minimizing τ_{tot}, or equivalently, by minimizing the distortion caused by τ_{tot} /8/. Moreover, for intensity-modulated optical signals carrying random or pseudo-random digital information, the distortion caused by first-order PMD can be readily measured with a high-speed monitor detector that integrates the received electrical power spectrum over a sufficiently large bandwidth.

First-order PMD gives rise to a 'spectral hole burning' in the received electrical signal, which can be described by a transfer function $S(f)$ with

$$S(f) = \sqrt{1 - 4\gamma(1-\gamma)\sin^2(\pi\,\tau_{tot} f)}\ ,$$

where γ and $(1-\gamma)$ are the fractions of optical power transmitted in the two PSP's corresponding to the residual DGD, τ_{tot} /9/. The electrical power spectrum, $P(f)$, of a pseudo-random non-return-to-zero (NRZ) digital signal detected after the PMD compensator is thus given by

$$P(f) \propto S^2(f)\ \mathrm{sinc}^2(\pi f / f_c),$$

where f_c is the clock frequency of the digital information signal and where we have neglected the D.C. component. Furthermore, to obtain the desired unambiguous feedback signal, P_f, for the POLCON and the DPDL, we reshape the power spectrum using a suitable filter function, $H(f)$, that emphasizes the low-frequency components below $f_c/4$, and then integrate the resulting spectrum over the entire frequency range. In particular, for $H(f) \equiv 1$ at $f \le f_c/4$ and $H(f) \equiv 0.5$ elsewhere, we find that

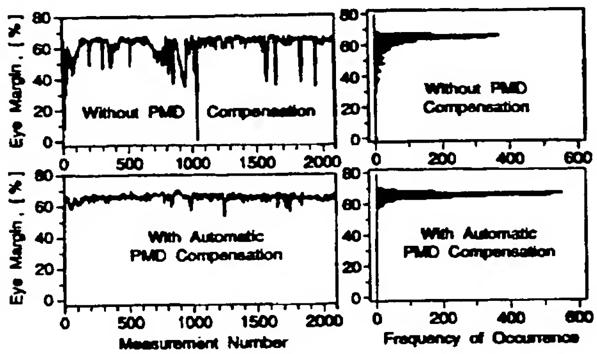
$$P_f = \int_0^{\infty} H(f)\,P(f)\,df$$

exhibits an absolute maximum at $\tau_{tot} = 0$ ps and decreases monotonically with increasing DGD, τ_{tot}, independent of γ. Hence, we may find the desired PSP-transformation for the POLCON and the proper time delay, τ_c, for the DPDL by searching for the maximal value of P_f. A suitable maximum-search algorithm for adjusting the lithium niobate POLCON used in our experiments is described in Ref. 10. A simpler one-dimensional version of this algorithm has been used to vary τ_c in the DPDL.

Experimental Results

Preliminary tests of the compensator have been conducted in the 10-Gb/s transmission system shown in Fig. 1, which employs a 10-km-long high-PMD fiber with a mean DGD of 50 ps. A 1.5-µm DFB laser integrated with an electro-absorption modulator generates the optical signal carrying a 10-Gb/s pseudo-random bit sequence of length $2^{31}-1$, which is transmitted through the high-PMD fiber and an optical amplifier before it passes through the PMD compensator. The compensator employs a fast lithium niobate POLCON, similar to the one described in Ref. 10, and a commercial, GPIB-bus-controlled DPDL (JDS Fitel PE3). A 3-dB splitter at the output of the compensator distributes the light to the high-speed monitor detector and to a conventional 10-Gb/s receiver, where a computer-controlled bit-error-rate (BER) analyzer evaluates the signal quality by measuring the receiver sensitivity at 10^{-10} BER as well as the relative eye margin (vertical eye opening) in the received signal for a BER of 10^{-7}.

Fig. 2: Measured eye margins in the received 10-Gb/s NRZ signal with and without PMD compensation versus time (left diagrams) and corresponding histograms (right).



The eye diagrams in Fig. 1 show an example of a severely distorted optical signal before and after the PMD compensator. Without PMD compensation, the eye is nearly completely closed, but after automatic DGD compensation of $\tau_c \approx 60$ ps it is wide open and almost free of distortions. A direct comparison of the system performance with and without PMD compensation can be obtained by blocking (and unblocking) one of the arms in the DPDL (in which case the POLCON automatically directs the light through the other arm). Fig. 2 displays the results of 2100 successive comparison measurements of the eye margins taken over a period of one week. Without PMD compensation, we observe severe degradations in the eye and, at times, even complete eye closure. It is clearly seen in Fig. 2 that these degradations are substantially reduced when the automatic PMD compensator is active, introducing varying time delays between 5 ps and 80 ps. In this case, the eye margin variations are less than 15 %. Work is under way to further improve the performance of the compensator.

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